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Measurement of the in-medium ϕ-meson width in proton-nucleus collisions

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Abstract

The production of ϕ mesons in the collisions of 2.83 GeV protons with C, Cu, Ag, and Au at forward angles has been measured via the $\phi \to K^+K^-$ decay using the COSY-ANKE magnetic spectrometer. The ϕ meson production cross section follows a target mass dependence of $A^{0.56\pm0.02}$ in the momentum region of 0.6–1.6 GeV/c. The comparison of the data with model calculations suggests that the in-medium ϕ width is about an order of magnitude larger than its free value.

Key words: ϕ meson production, nuclear medium effects.
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How the properties of light vector mesons change when they are in a strongly interacting environment has been a very active research field for several years [1,2], especially in connection with the question of the partial restoration of chiral symmetry in hot/dense nuclear matter.

The most interesting case is that of the $\phi(1020)$ meson, whose width in vacuum of 4.3 MeV/c^2 is narrow compared to those of other nearby resonances. Small modifications in medium should therefore be experimentally observable. Hadronic models [3,4,5] predict an increase in the width of low-momentum ϕ mesons in cold nuclear matter at nuclear saturation density by up to a factor of ten compared to the free value, whereas an insignificant mass shift is expected in both these models and in QCD sum rule studies [6,7].

Dileptons from $\phi \to e^+e^-/\mu^+\mu^-$ decays experience no strong final-state interactions in a nucleus so that any broadening of the ϕ spectral shape could be directly tested by examining dilepton mass spectra produced by elementary (γ, π, p) probes, provided the necessary cuts are applied on the low ϕ momenta [8,9]. These reactions are less complicated than heavy-ion collisions because they proceed in cold static matter of a well-defined density. Furthermore, it has been argued that the sensitivity of such reactions to in-medium changes of hadron properties should be comparable to those of nucleus-nucleus collisions [10].

Measurements of dilepton invariant mass distributions are, however, difficult due to the low branching ratios for leptonic decays. The KEK-PS-E325 collaboration measured e^+e^- invariant mass spectra in the ϕ region in proton-induced reactions on carbon and copper at 12 GeV and deduced a mass shift of 3.4% and a width increase by a factor of 3.6 at normal nuclear matter density for ϕ momenta around 1 GeV/c [9].

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An alternative method of studying the in-medium broadening of the ϕ meson has been considered both theoretically [11,12,13,14,15,16] and experimentally [17,18]. The variation of the ϕ production cross section with atomic number A depends on the attenuation of the ϕ flux in a nuclear target which, in turn, is governed by the imaginary part of the ϕ in-medium self-energy or width. In the low-density approximation, this width can be related to the ϕN total cross section. The advantage of this method is that one can exploit the large K^+K^- branching ratio ($\approx$ 50%) in order to identify the ϕ meson in production experiments on nuclear targets. Owing to the small energy release in this channel, any renormalization of the ϕ is very sensitive to the in-medium modification of kaons and antikaons, a subject which is also of great current interest.

An unexpectedly large in-medium ϕN total cross section of about 35 mb was inferred from measurements of K^+K^- pairs photoproduced on Li, C, Al and Cu targets at SPring8 [17]. In the low-density approximation, this implies a larger in-medium ϕ width than the KEK result [9]. Very recent data on ϕ photoproduction at JLab [18] also indicate a substantial in-medium broadening, though the precision in both cases is not sufficient to rule out the KEK result [9].

In an attempt to clarify the situation, measurements have been carried out at the ANKE-COSY facility [19,20] with a proton beam, detecting the ϕ through its K^+K^- decay. The main goal of these measurements was to obtain values of the so-called transparency ratio,

$$R = \frac{12\ \sigma_{pA\to\phi X'}}{A\ \sigma_{p\mathrm{C}\to\phi X}}\,, \tag{1}$$

normalized to carbon. Here $\sigma_{pA\to\phi X'}$ and $\sigma_{p\mathrm{C}\to\phi X}$ are inclusive cross sections for ϕ production in pA and pC collisions, respectively.

The experiment was performed with a 2.83 GeV proton beam, which is only a little above the ϕ production threshold in proton-nucleon collisions. The contributions from channels where there is an additional pion produced are therefore expected to be small. The targets used were light and medium nuclei C and Cu, as in the KEK [9] and SPring8 [17] measurements, but also the heavier Ag and Au, where distortion effects should be much stronger. The very narrow targets had thicknesses around 10–30 μm.

The COSY-ANKE spectrometer, located at an internal target position of COSY, is composed of three dipole magnets. $D1$ and $D3$ bend the direct proton beam from the undisturbed COSY orbit to the ANKE target and return it back, respectively. The analyzing magnet $D2$, placed between $D1$ and $D3$, deflects reaction products into the detection systems placed to the right and left of the beam to register, respectively, positively and negatively charged ejectiles, in this case K^+ and K^-. Positive kaons were first selected using a dedicated detection system that can pick out a K^+ against a π^+/p background that is 10^5 more intense [21]. The coincident K^- was subsequently

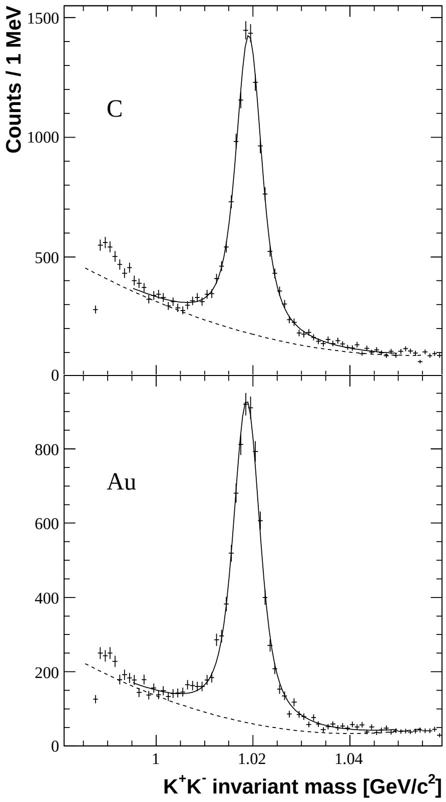

Fig. 1. Invariant mass distributions for K^+K^- pairs produced in pC and pAu collisions. The experimental data are not acceptance-corrected. The dashed lines are second-order polynomial representations of the backgrounds in the region of the ϕ peak.

identified from the time-of-flight difference between the stop counters in the negative and positive detector systems, these selections being carried out within $\pm 3\ \sigma$ bands [20].

The K^+K^- invariant mass spectra for the $pA \rightarrow K^+K^-X$ reaction look similar for the four targets and the results for the C and Au targets are presented in Fig. 1. In all cases there is a clear ϕ peak sitting on a background of non-resonant K^+K^- production together with a relatively small number of misidentified events.

The ANKE spectrometer only registers ϕ mesons at small laboratory polar angles, $0^\circ < \theta_\phi < 8^\circ$, over the limited momentum range, 0.6 GeV/c $< p_\phi <$ 1.6 GeV/c. To study the A-dependence of the transparency ratio, the numbers of ϕ events that fall within this acceptance window were first evaluated for every target. For this purpose, each mass spectrum was fitted by the sum of a Breit-Wigner function with the natural ϕ width, convoluted with a Gaussian resolution function with $\sigma = 1$ MeV/c^2, and a background function. This procedure therefore concentrates on the vast majority of the ϕ mesons that decay outside of the nucleus. Typical examples of the resulting fits are shown in Fig. 1.

The systematic uncertainties were studied by varying the fit region, binning, and mass scale, and changing the background curve from linear, quadratic to cubic. Their values for each ratio were then averaged and the final systematic uncertainty taken to be equal to 3σ. The number of reconstructed ϕ mesons for each target was between 7000 and 10000.

The relative luminosity for each target was derived by measuring simultaneously the fluxes of π^+ mesons with momenta between 475 and 525 MeV/c in the angular cone $\theta_\pi < 4^\circ$. Since the double-differential cross section for π^+ production has not been measured at 2.83 GeV, we parametrized the available data [22] at seven proton energies in the range 1–5.6 GeV in the form

$$\sigma_A = \sigma_0 A^\alpha. \qquad (2)$$

The interpolation of these fits to 2.83 GeV yielded an exponent α_π=0.38 ± 0.02, which allowed us to normalize the ratios of the numbers of measured ϕ mesons. Since the acceptance corrections in ANKE are essentially target-independent, this corresponds to the ratio of the cross sections for ϕ production in pA and pC collisions in the ANKE acceptance window. The resulting transparency ratios given in Table 1 correspond to production rates that follow the power law of Eq. (2) with $\alpha_\phi = 0.56 \pm 0.02$.

Table 1
The measured transparency ratio R of Eq. (1) in the acceptance window of the ANKE spectrometer. The first errors are statistical and the second systematic. The latter arise mainly from the evaluation of the numbers of ϕ events and the relative normalizations.

A/C	R
Cu/C	$0.479 \pm 0.011 \pm 0.035$
Ag/C	$0.387 \pm 0.009 \pm 0.033$
Au/C	$0.292 \pm 0.007 \pm 0.021$

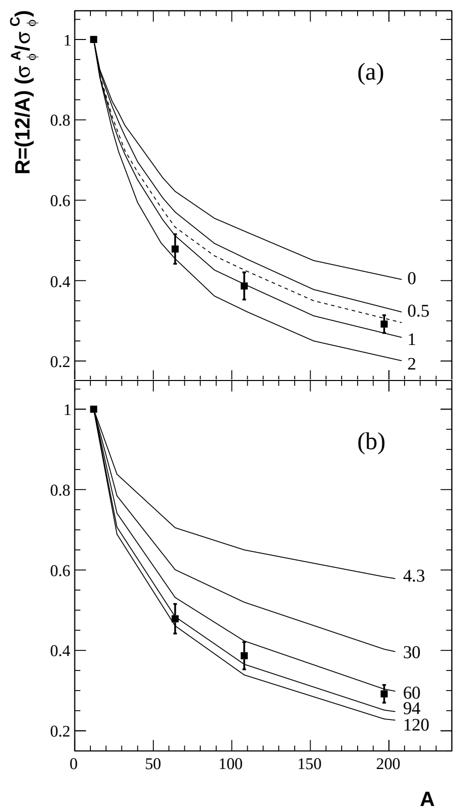

Fig. 2. Comparison of the measured transparency ratio R as a function of atomic number A with (a) the Valencia calculations [12], where the input width of 24 MeV/c^2 was multiplied by factors 0, 0.5, 1, and 2, as indicated. (b) Predictions of the Paryev model [16] for different ϕ widths. For the rest of the notations, see the text.

Any interpretation of the transparency ratio has to rely on a detailed theoretical treatment. In Fig. 2a we compare the experimental data with the results of calculations performed by the Valencia group within the local Fermi sea approach, using the eikonal approximation to account for the absorption of the outgoing ϕ meson [12]. The calculations have been done for $N = Z$ nuclei in a single-step ($pN \to pN\phi$) model, using predictions of the group [4,13] for the imaginary part of the ϕ self-energy in nuclear matter. This corresponds to a total width of $\Gamma = 28$ MeV/c^2 for a ϕ at rest at saturation density ρ_0. Figure 2a shows the predictions when this width, without the contribution from the free ϕ decay, is multiplied by factors of 0, 0.5, 1 and 2. It should be noted that these estimates were carried out over the whole available phase space. A fit to our data within this model yields the value of $\Gamma = 27^{+5}_{-3}$ MeV/c^2.

The contributions to ϕ production from two-step processes, with nu-

cleon and Δ intermediate states, have been estimated for the nominal width conditions [12] and these lead to an increase in the transparency ratio R, which is shown by the dashed line in Fig. 2a. If we take into account the isospin corrections for the $N \neq Z$ nuclei according to the prescription from Ref. [12], then a fit to our data within the extended model leads to $\Gamma = 45^{+17}_{-9}$ MeV/c^2. This about 50% greater than that predicted in [4], but is in good agreement with the theoretical estimates of Klingl *et al.* [5], who suggest $\Gamma \approx 45$ MeV/c^2.

In an alternative theoretical approach, Paryev [16] analyzed ϕ production in proton-nucleus reactions by considering primary proton-nucleon ($pp \to pp\phi$, $pn \to pn\phi$, $pn \to d\phi$) and secondary pion-nucleon ($\pi N \to \phi N$) processes in the framework of a nuclear spectral function model. This calculation takes into account the Fermi momentum of the struck target nucleon and the removal energy distribution. It uses the new measurements of the $pp \to pp\phi$ and $pn \to d\phi$ reactions [23,24] and estimates of the cross section difference between $pn \to pn\phi$ and $pp \to pp\phi$ [25]. The total in-medium width of the ϕ meson in its rest frame was assumed to be momentum-independent, as suggested by the Valencia calculations [13]. Results have been obtained for different values of this width, as indicated by the curves in Fig. 2b. It should be emphasized that the ANKE kinematical cuts on the laboratory ϕ momenta and production angles were included.

Fitting the data with the full Paryev model [16], yields a value of 73^{+14}_{-10} MeV/c^2 for the in-medium width of a moving ϕ meson in its rest frame at $\rho_0 = 0.16$ fm^{-3}. This corresponds to ≈ 50 MeV/c^2 in the nuclear rest frame when the ϕ has a momentum of 1.1 GeV/c, which is typical for the ANKE conditions. For a ϕ at rest in this frame at nuclear density ρ_0 this gives $\Gamma \approx 73$ MeV/c^2, in line with the original model assumptions [16].

In order to elucidate the discrepancies between the two models, a full phase space calculation within the approach of Ref. [16] has been repeated for $N = Z$ nuclei, keeping only the primary ϕ production processes $pN \to pN\phi$. With a ϕ total width of 30 MeV/c^2, the results are close to those obtained in [12] under similar conditions and represented by the line marked '1' in Fig. 2a. Moreover, it is found that the effects arising from the cuts imposed by the ANKE acceptance window are relatively minor. Hence the differences between the two theoretical approaches must be ascribed to the effects of secondary processes, which can have quite different A dependences [12,16,26]. The first results from the ongoing Rossendorf Boltzmann-Uehling-Uhlenbeck (BUU) calculations [27] lie between those of the two models. It is therefore clear that, in order to pin down ϕ medium effects better, it is necessary to improve our understanding of the ϕ production mechanisms in nuclei.

We can compare our results with those obtained in the SPring8 experiment [17]. The analysis of these

data within the Giessen BUU transport model shows a strong influence of the nuclear environment on the properties of the ϕ [14]. In the low-density approximation, the ϕN total cross section of 35^{+17}_{-11} mb extracted from these data corresponds to an in-medium width of about 80 MeV/c^2 for the ANKE conditions. The width of 50 MeV/c^2 deduced from our data on the basis of the approach of Ref. [16] is not inconsistent with this, taking into account the uncertainties in both results (see [28]). It is also in line with that deduced from the JLab measurements [18] but clearly larger than that found in the KEK experiment [9].

The direct fitting of the full models to the measured transparency ratios yields values of the total ϕ in-medium width of about 45 MeV/c^2 [12] and 73 MeV/c^2 [16], with the BUU calculations [27] falling between. In order to draw conclusions whether the observed ϕ width exhibits non-trivial medium effects, one has to compare this with naive expectations. Starting from a free ϕN cross section of $\approx$ 10 mb, the authors of Ref. [14] found, for vanishing ϕ momenta in the low-density approximation, a collision width of $\approx$ 18 MeV/c^2 at density ρ_0. Taking into account the free ϕ width of 4.3 MeV/c^2, this leads to a total width of $\approx$ 22 MeV/c^2. Independent of the model used for the analysis, our values clearly exceed this and leave significant space for non-trivial effects arising from the nuclear medium. Effects from ϕ/ω mixing [15], which have been invoked to explain non-spectator events in the $\gamma d \to \phi pn$ reaction [29], can be even more important in our case because the hadronic production of ϕ mesons is suppressed by the OZI rule [30]. It should, however, be stressed that the transparency ratio measurements do not allow one to disentangle the various mechanisms for medium modification.

In summary, we have performed a high statistics measurement of the transparency ratio for ϕ meson production with 2.83 GeV protons on C, Cu, Ag and Au targets. The production cross section was found to vary like $A^{0.56\pm0.02}$ for ϕ in the momentum range 0.6–1.6 GeV/c. Values of the ϕ width in nuclear matter were obtained by comparing the data with the two available models [12,16]. The results found indicate a substantial increase in the total ϕ width in the nuclear environment. Further theoretical and experimental efforts are needed to reach a better understanding of the phenomenon of ϕ renormalization in nuclear matter.

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